Update of the Present Bounds on New Neutral Vector Resonances from Electroweak Gauge Boson Pair Production at the LHC

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The model independent bounds on new neutral vector resonances masses, couplings and widths presented at arXiv:1112.0316 [1] are updated with an integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1} from ATLAS and $\mathcal{L} = 4.6$ fb^{-1} from CMS. These exclusion limits correspond to the most stringent existing bounds on the production of new neutral spin–1 resonances that decay to electroweak gauge boson pairs and that are associated to the electroweak symmetry breaking sector in several extensions of the Standard Model.

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I. INTRODUCTION

In this talk I update the bounds on new neutral vector resonances (Z') associated to the EWSB [1], that are common in many extensions of the Standard Model (SM). The updated bounds are derived using data from ATLAS (with integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1}) and CMS (with integrated luminosity of $\mathcal{L} = 4.6$ fb^{-1}) on W^+W^- pair production. Including a Z' the process is

$$pp \to Z' \to W^+W^- \to \ell^+\ell'^- \not{E}_T \tag{1}$$

where ℓ and ℓ' stand for electrons and muons. The bounds are presented in a model independent way as constraints on the relevant spin-1 boson effective couplings, mass and width. These exclusion limits correspond to the most stringent direct bounds that we are aware of on the production of a Z' that decay to electroweak gauge boson pairs. As an example, a Z' coupling with SM strength to light quarks and saturating the W^+W^- partial wave amplitudes can be excluded at the 2σ level for masses lighter than $\simeq 2$ TeV.

After describing the basic details of the model independent framework for the Z' properties as well as the details of the analyses in Section II, I present the model independent results using the updated data sets in Section III.

For the complete details of the simulations and analyses, as well as an extended discussion of the bounds and an example of how to translate the model independent bounds to a given model, the reader is referred to the original publication [1] that this update is based on.

II. FRAMEWORK AND ANALYSES DETAILS

In the analysis of the present bounds on the production of new neutral vector resonances we work in a framework [2, 3] where the relevant coupling of the process (1), the mass and the width are considered free parameters of the study. Inspired by models where the interactions of the new Z' are due to its mixing with the SM gauge bosons, we also assume that new vector resonance coupling to light quarks and W^+W^- pairs have the same Lorentz structure as the ones of the SM.

Defining the normalization factor $g_{Z'WW_{max}}$ as the $Z'W^+W^-$ coupling that saturates the partial wave amplitude for the process $W^+W^- \to W^+W^-$ by the exchange of a Z', [4]

$$g_{Z'WW_{max}} = g_{ZWW}\,\frac{M_Z}{\sqrt{3}M_{Z'}} \tag{2}$$

where $g_{ZWW} = g\ c_W$ is the strength of the SM triple gauge boson coupling, g is the $SU(2)_L$ coupling constant and c_W is the cosine of the weak mixing angle, we can define the relevant product of couplings of process (1) as the

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Experiment	Monte Carlo	ee	$e\mu$	$\mu\mu$
ATLAS	OUR ME-MC	0.51	0.70	0.92
CMS	OUR ME-MC	0.56	0.83	0.95

Table I: Overall multiplicative factors used to tune our simulator to the total number of events in the different flavour channels predicted by the ATLAS and CMS simulations.

combination:

$$G = \left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)\left(\frac{g_{Z'WW}}{g_{Z'WW_{max}}}\right), \tag{3}$$

here $g_{Z'q\bar{q}}$ and $g_{Z'WW}$ are the coupling constants of Z' to light quarks and W^+W^-, respectively, and $g_{Zq\bar{q}} = g/c_W$.

In this approach we treat G, the Z' width and its mass as free parameters, but for consistency with the decay of the Z' to light quarks and W^+W^- pairs we get the constraint [2]:

$$\Gamma_{Z'} \; > \; 0.27\,|G| \, \left(\frac{M_{Z'}}{M_Z}\right)^2 \text{GeV}\,, \tag{4}$$

Finally the cross section for the process (1) in this framework can be expressed as

$$\sigma_{\rm tot} = \sigma_{\rm SM} \, + \, G\, \sigma_{\rm int}(M_{Z'}, \Gamma_{Z'}) \, + \, G^2\, \sigma_{Z'}(M_{Z'}, \Gamma_{Z'}) \tag{5}$$

where the Standard Model, interference and new resonance contributions are labeled SM, int and Z' respectively.

The update of the bounds is based on the experimental analyses from ATLAS [5] and CMS [6]. There they analyzed the W^+W^- production through the final state given in Eq. (1). In our analyses we use the SM backgrounds that have been carefully evaluated by the experimental collaborations and we only simulate the Z' signal and its interference with the SM. Nevertheless we also simulate the SM production of W^+W^- pairs in order to use this process to tune and validate our Monte Carlo.

In the original analysis [1] two different simulators were used and it was checked that they led to compatible results with the experimental expectations for the SM W^+W^- pair production after tuning the simulators. We also checked that both methods gave consistent results in the production of Z' signals and interferences for different points of the parameter space. In order to update the bounds we use here what we labeled “OUR ME-MC”, that is based on the scattering amplitudes for the relevant processes obtained from the package MADGRAPH [7], while the evaluation was made with a *homemade* Monte Carlo that evaluates the process (1) at the parton level using the $\mathcal{O}(\alpha^4)$ signal matrix elements for the subprocesses $q\bar{q} \to \ell^+\nu\ell'^-\nu'$, with $\ell/\ell' = e, \mu$. We used CTEQ6L parton distribution functions [8] and the MADEVENT [7] default renormalization and factorization scales.

A. ATLAS analysis

In order to account for some of the features included in the ATLAS evaluation of the SM W^+W^- production, for instance highest available order simulations or detailed detector simulations, we tune our simulator to obtain a total cross section for the different flavor channels ee, $e\mu$ and $\mu\mu$ in the SM W^+W^- process equal to the one in Table 5 of the ATLAS analysis [5] after the same cuts have been implemented. The overall factors to tune our Monte Carlo are shown in Table I. The cuts in the ATLAS analysis are:

$$|\eta_e| < 1.37 \text{ or } 1.52 < |\eta_e| < 2.47 \text{ and } |\eta_\mu| < 2.4. \tag{6}$$

$$\Delta R_{ee} > 0.3 \text{ and } \Delta R_{e\mu,\mu\mu} > 0.2\,. \tag{7}$$

The transverse momentum cuts are slightly changed with respect to the original reference. For the update events are selected if the leading lepton in each channel and the electron in the $e\mu$ channel accomplish

$$p_T > 25 \text{ GeV}, \tag{8}$$

while for the rest of leptons

$$p_T > 20 \text{ GeV}. \tag{9}$$

The cuts on the relative missing energy have also been increased with respect to the original analysis:

$$\begin{aligned} &M_{ee,\mu\mu} > 15 \text{ GeV} \quad , \quad M_{e\mu} > 10 \text{ GeV}, \\ &|M_{ee,\mu\mu} - M_Z| > 15 \text{ GeV}, \\ &E_{T,\ rel}^{miss}(ee) > 50 \text{ GeV} \quad , \quad E_{T,\ rel}^{miss}(\mu\mu) > 55 \text{ GeV} \\ &\text{and } E_{T,\ rel}^{miss}(e\mu) > 25 \text{ GeV} \ , \end{aligned} \tag{10}$$

where $M_{\ell\ell}$ is the invariant mass of the lepton pair and the relative missing energy is defined as:

$$E_{T,\ rel}^{miss} = \begin{cases} E_T^{miss} \times \sin\Delta\phi_{\ell,j} & \text{if} \quad \Delta\phi_{\ell,j} < \pi/2 \\ E_T^{miss} & \text{if} \quad \Delta\phi_{\ell,j} > \pi/2 \end{cases} \tag{11}$$

with $\Delta\phi_{\ell,j}$ being the difference in the azimuthal angle ϕ between the transverse missing energy and the nearest lepton or jet. In a more detailed analysis jets would still have to be directly vetoed if $p_T > 30$ GeV and $|\eta_j| < 4.5$.

After our Monte Carlo has been tuned, we compare the transverse mass of the SM W^+W^- pair production from our simulator with the expectation from ATLAS in order to validate our Monte Carlo. Both distributions can be found in the left upper panel of Fig. 1. The results shown correspond to an integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1}. In the figure the stacked histograms for the different background processes as expected by ATLAS collaboration are shown together with our SM W^+W^- production expectation added to the ATLAS results for the rest of backgrounds (red dashed). It can be seen that our simulation approximates very well the ATLAS expectation.

As in the original analysis we use the normalization factors obtained from SM W^+W^- pair production to simulate the Z' signal and interference. As an illustration of the effects of including a new neutral vector resonance in the transverse mass spectrum of the process we show the expected M_T distribution for three different Z' new resonances after applying all the cuts and for a integrated luminosity of 4.7 fb^{-1} in the left lower panel of Figure 1. It can be seen that the effect of new spin–1 neutral resonances is characterized by an excess of events with respect to the SM expectations at the higher values of M_T.

Given this behavior we use the transverse mass spectrum to place constraints on the Z' properties. We construct a binned log-likelihood function based on the contents of the different bins in the M_T distribution and we assume the number of observed events follow independent Poisson distributions in each bin. The details of the statistical analysis can be found in the published reference [1]. The pulls [9] used to estimate the effect of systematic uncertainties are updated from Table 5 of [5] to:

$$\sigma_b^{st} \;=\; 0.026 \qquad \sigma_b^{sy} = 0.09 \tag{12}$$

$$\sigma_s^{st} \;=\; 0.005 \qquad \sigma_s^{sy} = 0.10 \tag{13}$$

The only change in the analysis with respect to the original publication [1] is that the upper limit of the ATLAS transverse mass distribution has been increased from 340 GeV to 360 GeV. We then performed two analyses: in the first one we computed the likelihood with the 16 transverse mass bins in [5] between $M_T = 40$ GeV and $M_T = 360$ GeV (*i.e.* $N_{AT}^{max} = 16$), while in the second one we added an extra 17th bin (*i.e.* $N_{AT}^{max} = 17$) where we assumed that the number of observed events and SM expected predictions are null and where we added the Z' expected contributions with $M_T > 360$ GeV.

B. CMS analysis

In the case of the CMS analysis the details of the simulation are analogous to the ATLAS ones. We tune our homemade Monte Carlo to account for the different details of the simulation by comparing the SM W^+W^- pair production in the ee, $e\mu$, and $\mu\mu$ channels with respect to the expectations presented in Ref. [6]. The cuts in the new CMS reference are:

$$|\eta_e| < 2.5 \text{ and } |\eta_\mu| < 2.4, \tag{14}$$

$$\Delta R_{ee} > 0.4 \text{ and } \Delta R_{e\mu,\mu\mu} > 0.3. \tag{15}$$

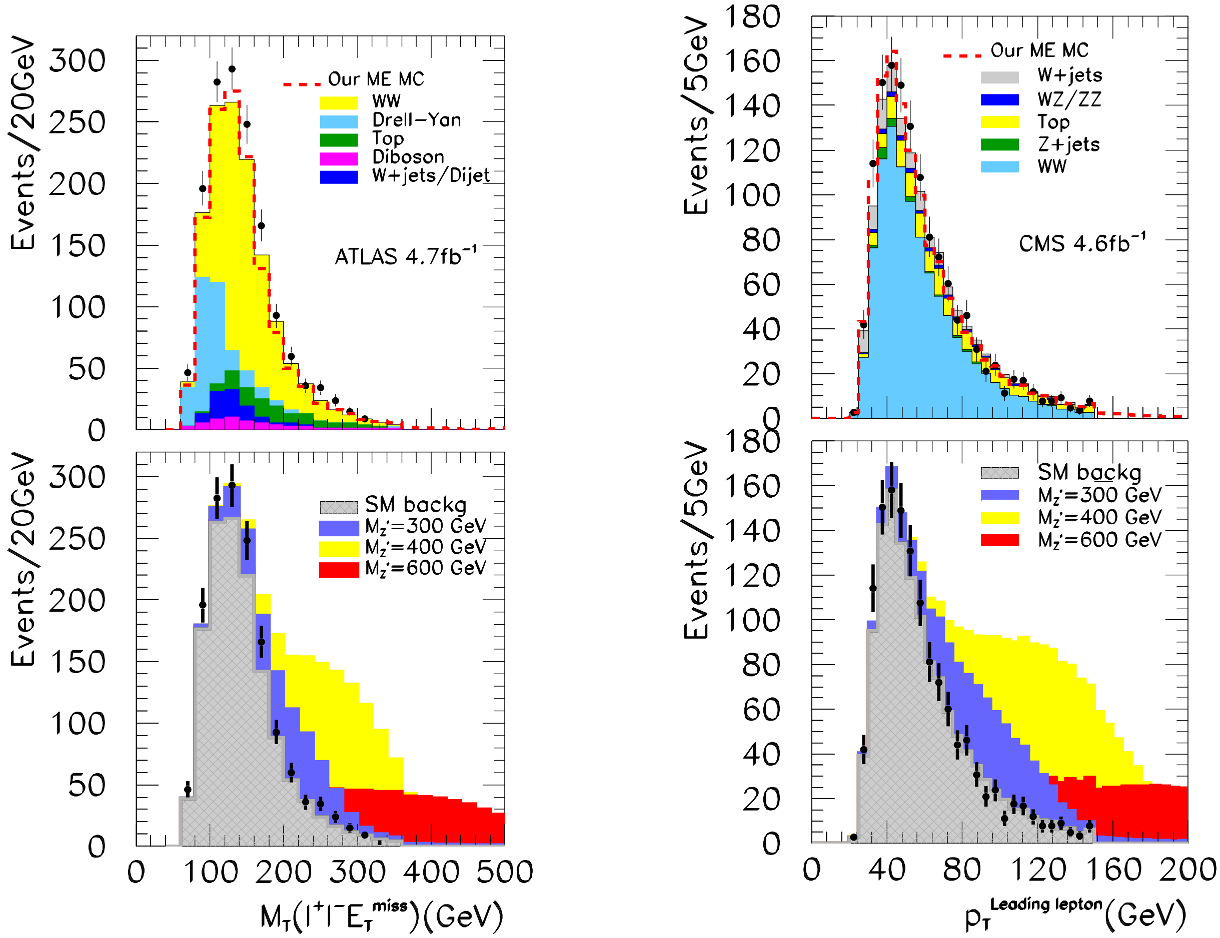

Figure 1: Left upper panel: Transverse mass distribution of the SM contributions to the process $pp \to \ell^+\ell'^-\not{E}_T$ calculated by ATLAS (colored histograms) together with the number of observed events by ATLAS (points with error bars) and the performance of OUR ME-MC (red dashed). The results shown correspond to an integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1}.
Left lower panel: Transverse mass distribution of the total SM contribution to the process $pp \to \ell^+\ell'^-\not{E}_T$ (gray hashed) together with the total expected number of events including a Z' of 300 GeV with $G = 0.5$ (blue), a Z' of 400 GeV with $G = 1$ (yellow) and a Z' of 600 GeV with $G = 1$ (red). For the three masses $\Gamma_{Z'} = 0.06 M_{Z'}$. We include also the ATLAS observed spectrum. Integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1}.
Right upper panel: Leading lepton transverse momentum distribution of the SM contributions to the process $pp \to \ell^+\ell'^-\not{E}_T$ calculated by CMS (colored histograms) together with the number of observed events by CMS (points with error bars) and the performance of OUR ME-MC (red dashed). The results shown correspond to an integrated luminosity of $\mathcal{L} = 4.6$ fb^{-1}.
Right lower panel: Transverse momentum of the leading lepton for the total SM contribution to the process $pp \to \ell^+\ell'^-\not{E}_T$ (gray hashed) together with the total expected number of events including a Z' of 300 GeV with $G = 0.5$ (blue), a Z' of 400 GeV with $G = 1$ (yellow) and a Z' of 600 GeV with $G = 1$ (red). For the three masses $\Gamma_{Z'} = 0.06 M_{Z'}$. We include also the observed distribution of events in CMS. Integrated luminosity of $\mathcal{L} = 4.6$ fb^{-1}.

The leptons need to verify also:

$$\begin{aligned} & p_T^{\text{leading}} > 20 \text{ GeV}, \\ & p_{T\ e\mu}^{\text{subleading}} > 10 \text{ GeV},\ p_{T\ ee,\mu\mu}^{\text{subleading}} > 15 \text{ GeV} \\ & M_{ee,\mu\mu} > 20 \text{ GeV} \quad \text{and} \quad M_{e\mu} > 12 \text{ GeV}, \end{aligned} \tag{16}$$

$$|M_{ee,\mu\mu} - M_Z| > 15 \text{ GeV},$$
$$E_{T,\ rel}^{miss}(ee,\mu\mu) > 40 \text{ GeV} \quad \text{and} \quad E_{T,\ rel}^{miss}(e\mu) > 20 \text{ GeV}.$$

Comparing the new and old CMS analyses, one can notice that the requirement on the transverse momentum of the subleading lepton has been increased in order to reduce the low-mass $Z/\gamma^* \to \ell^+\ell^-$ contribution and the W+jets background in the ee and $\mu\mu$ channels. Furthermore, the cut on the minimum $M_{ee,\mu\mu}$ is also stronger in order to suppress contributions from low mass resonances. Finally a new cut in the transverse momentum of the system formed by the pair of leptons has been included in the new CMS reference for all three channels ee, $e\mu$ and $\mu\mu$:

$$p_T^{\ell\ell} > 45 \text{ GeV}. \tag{17}$$

The aim of this new cut is to further reduce the contribution of Drell–Yan and fake background contamination. It is worth noting that the jet veto and the cut on the angle in the transverse plane between the dilepton system and the most energetic jet with $p_T > 15$ GeV would still have to be directly applied when doing a more detailed simulation.

As in the ATLAS case the normalization factors needed to tune our simulator after applying all the cuts are shown in Table I. In order to validate our simulator we compare the SM background expectations from CMS collaboration and the sum of our SM W^+W^- pair production simulation to the rest of CMS backgrounds (red dashed) as a function of the transverse momentum of the leading lepton in the right upper panel of Fig. 1. Our simulation approximates very well the CMS expectations. The effect of introducing new neutral vector resonances can be observed in the right lower panel of the same Fig. 1. For the simulation of the Z' signal and the interference we employed the same normalization factors obtained from the W^+W^- SM production for the channels ee, $e\mu$, and $\mu\mu$. The presence of the new Z' enhances the contribution at the higher values of the transverse momentum of the leading lepton. Consequently the exclusion limits on the production of a Z' were extracted using a binned log-likelihood function based on the contents of the bins of the transverse momentum distribution of the leading lepton [1].

As in the original reference we performed two analysis. First we calculated the binned log–likelihood function using the events in the bins shown in the CMS image. That means the event rates in the 26 leading lepton transverse momentum bins between 20 GeV and 150 GeV (*i.e.* $N_{CMS}^{max} = 26$). In the second analysis we added an extra bin where we included the number of observed events and background expectations that are left with values higher than 150 GeV. These values can be obtained from comparing the quantities read from the images with the values quoted in Table 2 of [6]. In this extra bin we also added the expected contributions from the Z' with $p_T^{\text{leading}} > 150$ GeV (*i.e.* $N_{CMS}^{max} = 27$).

C. Combined Analysis

In order to get more stringent bounds on the production of a Z' that decays into electroweak gauge boson pairs we combined the ATLAS and CMS results by constructing the combined log-likelihood function assuming conservatively that the ATLAS and CMS systematic uncertainties are uncorrelated.

In all cases we set the 2σ exclusion limits (2σ, 1 d.o.f) on G by maximizing the corresponding likelihood function (or equivalently minimizing the χ^2) with respect to G for each value of $M_{Z'}$ and $\Gamma_{Z'}$ and imposing

$$|\chi^2(M_{Z'}, G, \Gamma_{Z'}) - \chi^2_{\min}(M_{Z'}, \Gamma_{Z'})| > 4 \, . \tag{18}$$

III. RESULTS

All the 2σ exclusion limits on new neutral vector resonances that decay to electroweak gauge boson pairs are shown in the plane $G \otimes M_{Z'}$ for three possible values of the Z' width $\Gamma_{Z'}/M_{Z'} = 0.01$, 0.06 and 0.3.

The bounds for the ATLAS analysis, corresponding to the study of the transverse mass spectrum observed with an integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1} are presented in Fig. 2. There we can distinguish three different regions: the grey shadowed regions in the upper right (lower right) of the upper (lower) panel correspond to points excluded by requiring the consistency of the total decay width of a Z' with its decay to light quarks and SM W^+W^- pairs as expressed in Eq. (4). The red solid regions were derived making the analysis with $N_{AT}^{max} = 16$ bins, between $M_T = 40$ GeV and $M_T = 360$ GeV, while the purple hatched regions contain the points excluded when the extra bin accounting for values of transverse mass $M_T > 360$ GeV is included, $N_{AT}^{max} = 17$. One can observe that the bounds are stronger for narrow resonances, while including the extra bin has a bigger impact for a wider and heavier Z'. Furthermore the effect of the interference, that can be observed by comparing the upper and lower panels, is noticeable only for wider and lighter new resonances, as expected from the interference term being roughly proportional to $\Gamma_{Z'}/M_{Z'}$.

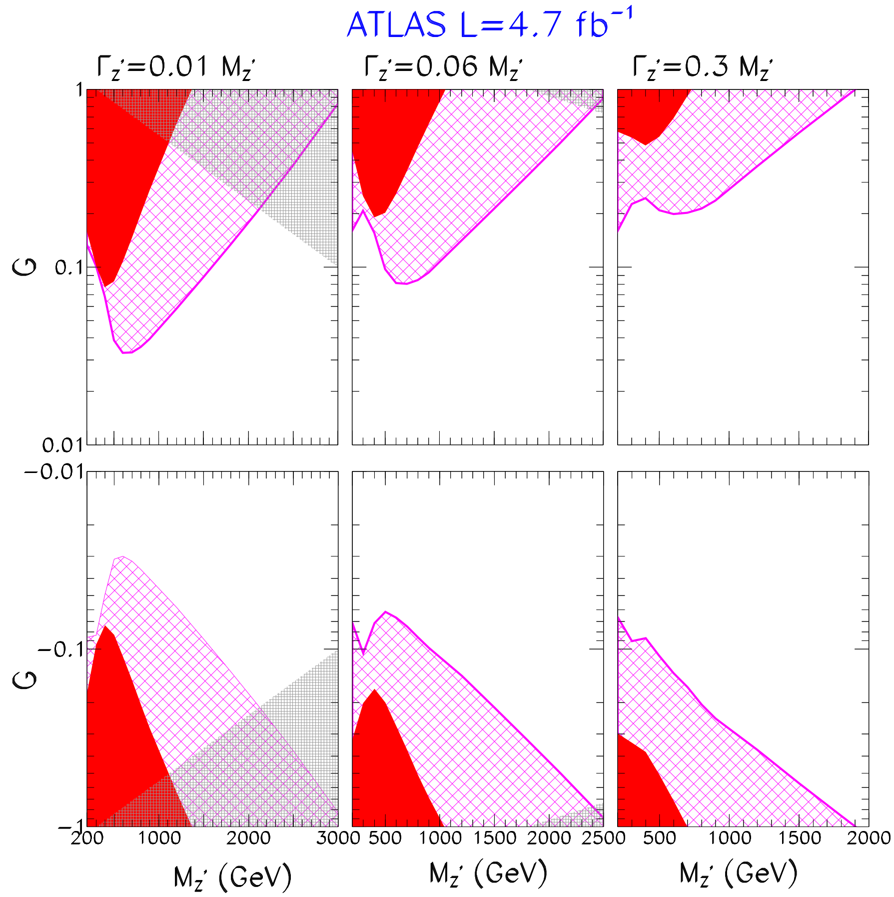

Figure 2: 2σ exclusion limits on the production of a Z' from our analysis of the M_T distribution measured by ATLAS with $\mathcal{L} = 4.7$ fb^{-1} and for three values of $\Gamma_{Z'}/M_{Z'} = 0.01$, 0.06 and 0.3 (left, center and right panels respectively). The red solid regions are derived using the log-likelihood function with $N_{AT}^{max} = 16$. The purple hatched regions are derived using the log-likelihood function with $N_{AT}^{max} = 17$. The shadowed regions in the upper (lower) right corner of the upper (lower) panels represent the excluded values by the condition Eq. (4).

In the CMS case the 2σ exclusion limits on the production of a Z' derived from the analysis of the $p_T^{\rm leading}$ distribution measured with an integrated luminosity of $\mathcal{L} = 4.6$ fb^{-1} can be seen in Fig. 3. The bounds are very similar to the ATLAS case. The only difference is in the shape of the exclusion limits without the extra bin. This is due to the fact that within the range of the kinematic values and the kinematic variables used CMS is more sensitive than ATLAS to the lightest masses when no extra bin is included.

Finally the 2σ exclusion limits on the production of new Z' from the combination of the analysis of the transverse mass spectrum in ATLAS with an integrated luminosity of $\mathcal{L} = 4.7$ fb^{-1} and the $p_T^{\rm leading}$ distribution spectrum in CMS with $\mathcal{L} = 4.6$ fb^{-1} are shown in Fig. 4. These are the strongest existing direct bounds on the production of new neutral vector resonances that decay to electroweak gauge boson pairs. Comparing to the original reference [1] where $\mathcal{L} = 1.02$ fb^{-1} from ATLAS and $\mathcal{L} = 1.55$ fb^{-1} from CMS were used, we can observe that now from our combined analysis with 17 and 27 bins from the ATLAS and CMS distributions respectively, a narrow resonance of any mass with $\Gamma_{Z'}/M_{Z'} = 0.01$ and that saturates the partial wave amplitude for the process $W^+W^- \to W^+W^-$ is excluded at 2σ level if its coupling to the light quarks is larger than 19% of the SM $Z\bar{q}q$ coupling. From the extended analysis we can also see that a new neutral vector resonance that saturates the partial wave amplitude for the process $W^+W^- \to W^+W^-$ and couples to light quarks with SM strength is completely excluded for $\Gamma_{Z'}/M_{Z'} = 0.01$ and $\Gamma_{Z'}/M_{Z'} = 0.06$, while for a wider resonance, $\Gamma_{Z'}/M_{Z'} = 0.3$, it is excluded for masses up to 2 TeV.

As it is shown in the original analysis [1], the bounds there are already generically stronger than the ones obtained by the CDF collaboration analyzing WW production at the Tevatron [10]. Looking at the exclusion limits figures presented here we can observe that with the new $\mathcal{L} = 4.7$ fb^{-1} and $\mathcal{L} = 4.6$ fb^{-1} data sets from ATLAS and CMS respectively, the exclusion limits not only are extended to heavier masses but also for a given mass and width the

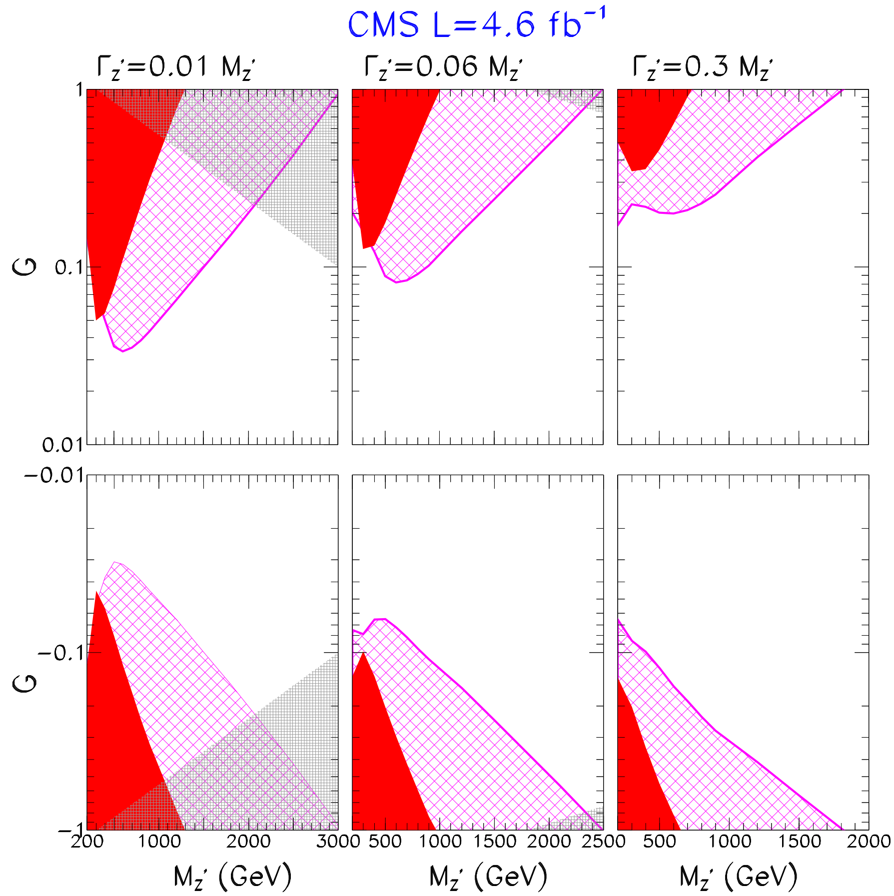

Figure 3: 2σ exclusion limits on the production of a Z' from our analysis of the $p_T^{\rm leading}$ distribution measured by CMS with $\mathcal{L} = 4.6$ fb^{-1}. The left, center and right panels correspond to three values of $\Gamma_{Z'}/M_{Z'} = 0.01$,0.06 and 0.3 respectively. The red solid regions are derived using the log-likelihood function with $N^{max}_{CMS} = 26$. The purple hatched regions are derived using the log-likelihood function with $N^{max}_{CMS} = 27$. The shadowed regions in the upper (lower) right corner of the upper (lower) panels represent the excluded values by the condition Eq. (4).

couplings excluded are extended to values around 60% of the original exclusion limits.

All the 2σ exclusion limits on the production of a new Z' are presented in a model independent way. Consequently they can be translated to many different EWSB models. A detailed example of how to translate the bounds to a given model can be found in the published analysis [1].

To summarize, in this talk the update of the bounds on new neutral vector resonances in electroweak gauge boson pair production using $\mathcal{L} = 4.7$ fb^{-1} from ATLAS and $\mathcal{L} = 4.6$ fb^{-1} from CMS is presented. The exclusion limits on the production of a Z' associated with the EWSB sector are placed analyzing the kinematic distributions of the $pp \to \ell^+\ell'^-\not{E}_T$ events. The model independent results correspond to the most stringent exclusion limits available on the production of a Z' that decay to SM W^+W^- pairs, well exceeding the limits from Tevatron and the previous LHC limits.

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[1] O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, Phys. Rev. D **85**, 055019 (2012) [arXiv:1112.0316 [hep-ph]].
[2] A. Alves, O. J. P. Eboli, D. Goncalves *et al.*, Phys. Rev. **D80**, 073011 (2009). [arXiv:0907.2915 [hep-ph]].
[3] O. J. P. Eboli, C. S. Fong, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, Phys. Rev. **D83**, 095014 (2011). [arXiv:1102.3429 [hep-ph]].

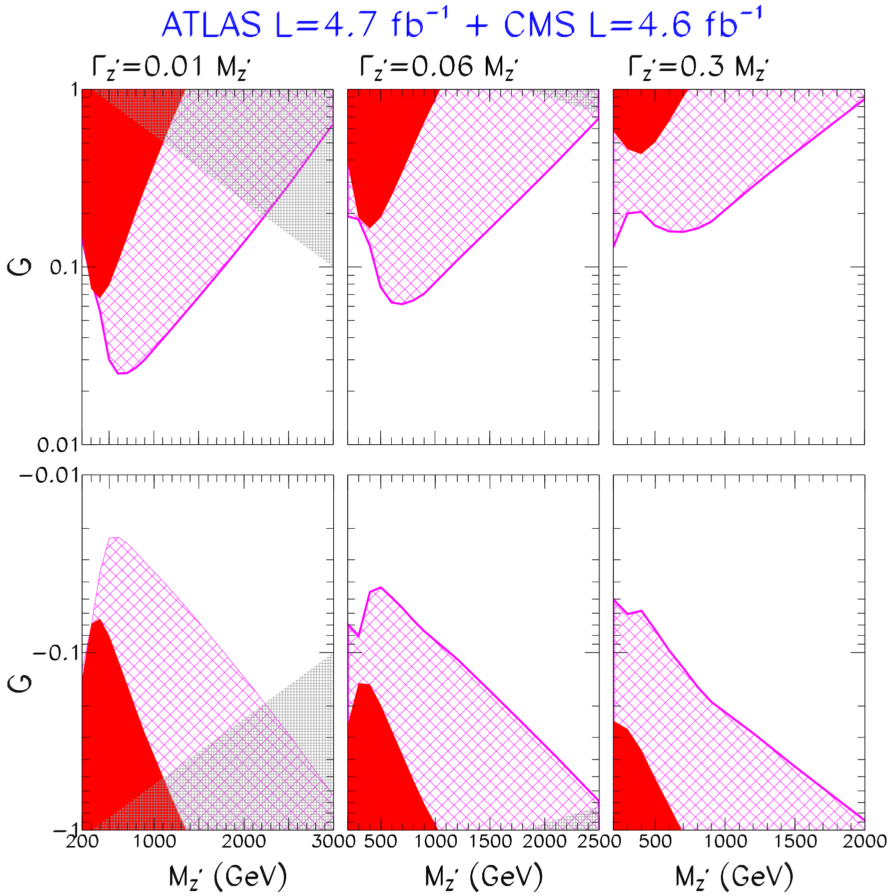

Figure 4: 2σ exclusion limits on the production of a Z' from our combined analysis of the measured M_T distribution in ATLAS with $\mathcal{L} = 4.7$ fb^{-1} and the p_T^{leading} distribution measured by CMS with $\mathcal{L} = 4.6$ fb^{-1}. The red solid (purple hatched) regions are derived using the combined log-likelihood function with 16 and 27 (17 and 27) bins of the ATLAS and CMS distributions respectively. The shadowed regions in the upper (lower) right corner of the upper (lower) panels represent the excluded values by the condition Eq. (4).

[4] A. Birkedal, K. Matchev and M. Perelstein, Phys. Rev. Lett. **94**, 191803 (2005) [arXiv:hep-ph/0412278]; H. J. He *et al.*, Phys. Rev. D **78**, 031701 (2008) [arXiv:0708.2588 [hep-ph]]; T. Ohl and C. Speckner, Phys. Rev. D **78**, 095008 (2008) [arXiv:0809.0023 [hep-ph]].

[5] The ATLAS Collaboration, ATLAS-CONF-2012-025 `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-025/`

[6] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710**, 91 (2012) [arXiv:1202.1489 [hep-ex]]. `https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11024TWiki`

[7] T. Stelzer and F. Long, Comput. Phys. Commun. **81** (1994) 357; F. Maltoni and T. Stelzer, J. High Energy Phys. **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[8] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

[9] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, Phys. Rev. **D66**, 053010 (2002). [hep-ph/0206162], M. C. Gonzalez-Garcia, M. Maltoni, Phys. Rept. **460**, 1-129 (2008). [arXiv:0704.1800 [hep-ph]].

[10] T. Aaltonen *et al.* [The CDF Collaboration], Phys. Rev. Lett. **104**, 241801 (2010). [arXiv:1004.4946 [hep-ex]].